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ABSTRACT: In recent years, the increased frequency of extreme rainfall events has led to many bridge failures throughout the UK and Ireland. Particularly vulnerable are short span bridges, which typically include arch structures, where abutments and piers are quickly scoured at their foundations. Several bridges have collapsed under flood conditions and, recently, such events have occurred in Northern England during the floods during the latter part of 2015. This paper is the result of an on-going experimental investigation, funded by The Royal Society, where arch bridge scale models are subjected to pressurised flow. Results demonstrate the nature of the upstream and downstream velocity distributions, and resulting scour profiles. The study provides an insight into the significance of pressurised flow on the depth and extent of scour when compared to normal open channel conditions. Measurements of velocities were taken using Acoustic Doppler Velocimeter (ADV), where significant increases in bed velocities are experienced as the flow passes under the arch. Scour depth was measured using a 3D laser scanner, which verified the shape of the resulting scour hole. The outcome of this paper is the demonstration of the severity of scour within the vicinity of an inundated arch bridge structure. It highlights the likely risks to long term stability, identifying depth locations to consider in relation to protection against local scour.

KEY WORDS: Bridge; Flooding; Scour.

1 INTRODUCTION

There is now significant evidence, which suggests that climate change is having a major impact on infrastructure both presently and in the near future (Committee on Climate Change, [1]). These impacts include combination of social, economic and environmental. As the climate changes, weather patterns are becoming less predictable, and with more extreme events taking place e.g. rain and snow falls, it is increasingly difficult for infrastructure engineers to design structures to cope with these extreme occurrences. These extreme weather cycles create more rain, which causes rivers to flood. This has a large impact on the existing structures in the river and one aspect, which is not fully understood, despite extensive research, is hydraulic scour, as reported by the UK Roads Liaison Group. This is also not helped by the limited UK/Ireland standards applied within the Design Manual for Roads and Bridges (DMRB) in relation to designing for hydraulic action [2]. This has not been revised since 1994. However, current standards for inspection have been updated to take into account a risk based assessment procedure within DMRB [3]. The failure of these bridges may be because of the complex interplay of mankind and the environment, which is particularly hard to understand and model, hence the need for further work.

CIRIA C742 [4] states 'scouring is the removal of sediment primarily caused by fast moving water that lifts the material and transports it downstream'. It is potentially catastrophic when bridges, which have shallow foundations, are then undermined, thus severely reducing the structural integrity of the bridge. Ryan et al, [5] noted that in November 2009, the UK and Ireland were subjected to extraordinarily severe weather conditions for several days. The rainfall was logged as amongst the highest levels of rainfall ever recorded within the UK and, and as a direct consequence, unprecedented flooding occurred. In Cumbria, this flooding led to the loss of one life and the collapse of three road bridges, which were generally 19th century masonry arch bridges, with relatively shallow foundations.

As stated previously, Highways Agency published a revision to BA 74/06 "Assessment of Scour at Highway Bridges" in 2012. The new revision (i.e. BD 97/12) [3] advises on how to determine the level of risk associated with scour effects. Highways Agency also still refers to BA59/94 "The Design of Highway Bridges for Hydraulic Action" [2] provides design guidance based on references from publications prior to 1994. The significance of these reference dates is that the reference material cited does not take into account the current situation in relation to climate change.

In the UK, the above standards clarify that the recommended design guidance documentation for highway bridges does not provide advice on predicting/designing to reduce scour under pressurized flow conditions. Hence, the rationale behind this paper towards considering the effects of flood flows/inundation on existing structures, with particular emphasis on structures with limited spans. The impact of this research will become significant to stakeholders and designers, where the finding will inform maintenance guidance and provide design advice to engineers responsible for maintaining the life-span of this critical infrastructure by gaining full knowledge of the bridge behaviour under pressurized conditions.

2 BACKGROUND RESEARCH

2.1 Bridge Hydraulics and Scour

Several authors have investigated the hydraulics of flow in the vicinity of an arch bridge. The majority of this work was carried out for normal flow conditions, where arch inundation was not considered. Previous authors were also interested in the prediction of afflux and discharge through the bridge structure. However, when the soffit of a bridge is submerged there were two specific conditions (1) Sluice Flow and (2) Drowned Orifice flow. Equation 1 is proposed for sluice flow and equations 2 & 3 are proposed for drowned orifice flow. These equations have been previously reported in the FHWA publication of the Hydraulic Design of Safe Bridges [6]:

$$Q = C_d a_w \left[2g\left(Y_u - \frac{Z}{2} + \frac{\alpha_u V_u{}^2}{2g}\right)\right]^{1/2} \quad (1)$$

$$Q = C_d a_w (2g\Delta H)^{1/2} \quad (2)$$

where C_d (= 0.35 to 0.6) is the discharge coefficient, a_w is the total area of the opening flowing full (m^2), Y_u is the upstream depth (m) and Z is distance between the soffit and the bed level (m). Equation 3 defines ΔH as:

$$\Delta H = \left[\left(Y_u - \frac{Z}{2} + \frac{\alpha_u V_u{}^2}{2g}\right) - \left(Y_d - \frac{Z}{2} + \frac{\alpha_d V_d{}^2}{2g}\right)\right] \quad (3)$$

The subscripts u and d denote upstream and downstream respectively. The above equations have never been tested for Arch Bridges, and the only equation for predicting discharge was proposed by Biery & Delleur [7] as:

$$Q = C_d\sqrt{2g}\,\frac{17}{24}\,y_1{}^{3/2} b \begin{bmatrix} 1 - 0.1294\left(\frac{y_1}{r}\right)^2 \\ -0.0177\left(\frac{y_1}{r}\right)^4 \end{bmatrix} \quad (4)$$

where y_1 is the depth of flow at the section of maximum backwater (m), b is the span width at the spring line of the arch (m) and r is the radius of curvature of the arch (m). The limitation of Equation 4 is that the C_d value must be determined from Tables within the publication itself, and the same equation determines discharge for both sluice and orifice conditions, where no clear evidence from tests is demonstrated within the publication.

The above equations have been widely used to predict bridge afflux and have also been utilised to determine the flow through the bridge constriction and hence the average flow velocity through the same. As the velocity increases within a bridge constriction, formulae were developed to determine scour depth as a function of the relationship between upstream average velocity (v_u) and the average velocity through the constriction (v_a). A value for v_a is determined from Equation 4 for an arch bridge.

With knowledge on how to determine the y_1 upstream depth value, it was possible to determine the depth of scour by applying the Arneson & Abt [8] equation:

$$\frac{y_s}{y_1} = -5.08 + 1.27\left(\frac{y_1}{H_b}\right) + 4.44\left(\frac{H_b}{y_1}\right) + 0.19\left(\frac{V_a}{V_c}\right) \quad (5)$$

where v_c is the critical velocity for incipient motion (m/s), H_b is the distance from the soffit of the bridge to the initial bed level (m) and y_1 is another term for the upstream bed level (m). This equation has previously been widely utilized and has become known as the HEC-18 equation, as published by Richardson & Davis [9]. However, Lyn [10] had identified that there were problems with the validity of equation 5 and proposed an alternative predictive relationship where y_s is the final depth of scour (m):

$$\frac{y_s}{y_1} = min\left\{0.105\left(\frac{V_a}{V_c}\right)^{2.95}, 0.5\right\} \quad (6)$$

These revised equations have been widely used to predict pressurized scour in the USA to date.

2.2 Experimental Set-up & Data Acquisition.

Previous authors, including Arneson & Abt [8], Richardson & Davis [9] and Gou [11] carried out extensive physical modelling on sediment scouring. However, there was no evidence of attempting to understand the flow velocities within the vicinity of the bridges. Each author cited the work of early authors such as Laursen [12] and in relation to examining critical velocity of sediment (v_c), but made little attempt to carry out any work in establishing a relationship between scour depth and velocity within the vicinity of the bridge, under pressurised flow. There seems to be an emphasis on upstream average critical velocity and the average velocity through the bridge. These are averaged, based on continuity equation, and using Equations 1-4, depending on the physical conditions.

The present investigation considers the magnitude of these velocities through an arch bridge, in order to gain a better understanding of the nature of flow through a pressurised arch. Velocity measurements are taken by using a SonTEK 2D Acoustic Doppler Velocimeter (ADV), with a sampling frequency of 50 Hz. Measurements were taken for an initially flat bed, stabilized by using an Epoxy Resin treatment. Following this, the scour holes were allowed to fully develop to an approximate equilibrium stage of erosion (approx. 120 mins), and measurements taken for the purposes of making comparisons with the flat bed condition. A grid system is used both upstream and downstream of the arch models, where the grid density for velocity measurement (ADV probe) was increased within the vicinity of the higher velocities to that of a 20 x 20mm grid. Outside the confines of the arch, the grid was increased to a density of 50 x 50 mm.

Velocity measurements were taken on the XY plane at six positions (1) 1000 mm upstream of the flow entering the bridge arch, (2) at 500 mm upstream of the flow entering the bridge arch, (3), 50 mm upstream of the flow entering the arch, (4) 50 mm downstream of the flow exiting the arch, (5) 500 mm downstream of the flow exiting the bridge arch and (6) 1000 mm downstream of the flow exiting the bridge arch.

The data was then analyzed qualitatively to determine how the velocity profiles varied with distance through the arch.

All of the uPVC model bridge experiments have been carried out within a 10-metre long Perspex channel of dimensions 760 mm × 250 mm. The overall depth at the recess section was 480 mm. Water is supplied via a reservoir and 2 No. impeller pumps and is capable of supplying 100 l/s to the upstream supply reservoir.

For scour tests, a recess was constructed within the channel for the purposes of these experiments to a total depth of 230 mm. A bridge model structure was inserted half way down the channel. The abutment length (i.e. model road width) is 280 mm for these experiments. The width is 750 mm with a 365 mm span. This is reported in Ryan et al [3].

3 EXPERIMENTAL RESULTS & DISCUSSION

3.1 Velocity profiles in the vicinity of the arch bridge.

Equations 1-4 provide methods for determining discharges and average velocities. However, the average velocities are not representative of the near bed conditions, where high levels of turbulence and an upstream head (due to backwater effects) produces sluice conditions.

Figure 1(a) shows the upstream end of an experiment on a 365 mm arch, with 45^0 wing walls at a flow of 40 l/s. For this experiment there is a total of 60 mm head above the barrel of the arch.

Figure 1(a): Upstream conditions for bridge experiment.

Figure 1(b) show the downstream condition, where the flow velocities are much more rapid and depths are supercritical.
It can be clearly shown that there is a considerable likelihood that excessive damage to the channel bed is likely in these conditions, especially with the likes of a masonry arch, where mortar joints can also experience wash-out.

Figure 2 shows the increase in channel centreline velocity versus distance upstream/downstream of a model arch for one of the experiments. These experiments are taken for a flat/fixed bed scenario to provide some understanding of the bridge hydraulics.

The velocity profiles are taken on the upstream side (U/S) at a maximum depth of 200 mm from the bed. This is 20 mm below the water surface to allow full submergence of the ADV. On the downstream (D/S) side, velocity measurements are taken from 150 mm above the bed. This is due to the fact that the difference in level between upstream and downstream is 50 mm.

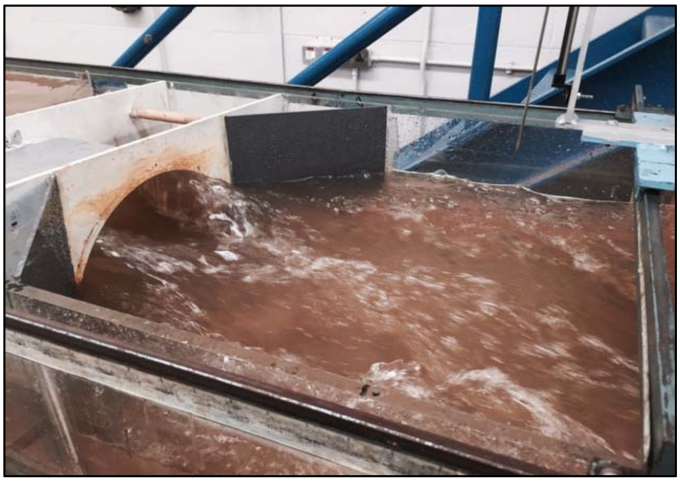

Figure 1(b): Downstream conditions for bridge experiment.

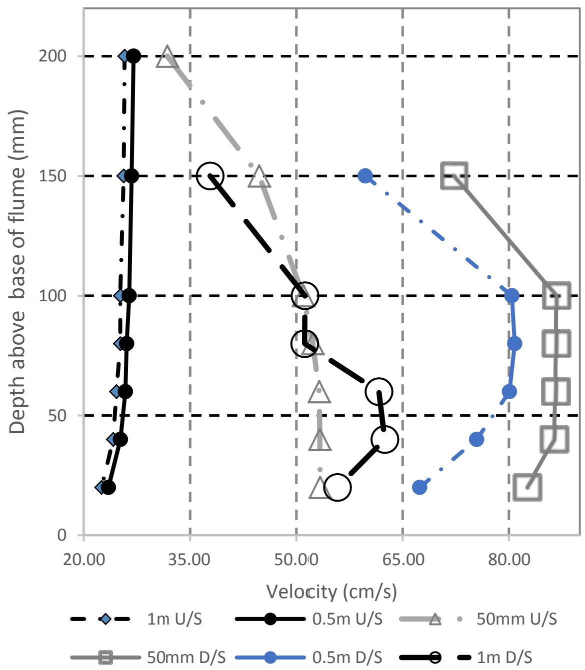

Figure 2: Centreline velocity distributions upstream and downstream of the model arch bridge.

At 1000 mm (1 m) and 500 mm (0.5 m) upstream of the bridge, it is clear that the effect of the bridge and wing walls is almost negligible when considering the velocities at the centreline of the channel. The increase becomes appreciable when it reaches a point up to 50 mm upstream of the bridge opening. Velocity increases are demonstrated from 200 mm upstream and this is approximately where local scour commences. At 50 mm upstream, the maximum velocity has increased from 28 cm/s (0.28 m/s) to 62 cm/s (0.62 m/s), and has moved from near surface to approximately 40mm above the bed. Near bed velocities are at approximately 0.55m/s, which is easily in excess of the critical velocity for sediment transport. As the experiment moves downstream the maximum velocities approach 0.9 m/s and then gradually decrease to 0.55 m/s at 1 m downstream.

3.2 Scour Profiles.

Scour depth tests have been carried out with several combinations of arch barrel sizes, wing wall configurations and sediment sizes. Depending on the experimental conditions, the scour profiles slightly differ. In Ryan et al [5] it was reported in the absence of wing walls that the maximum depth of scour occurred at the upstream face of the abutment. When considering the presence of wing walls, there were slightly lower upstream depth results. The improved conveyance of flow inhibited the upstream turbulence (eddies) and led to a slightly different scouring pattern. The upstream scour is shown in Figure 3.

Figure 3: Scour hole for 40 l/s with 22.5^0 wing walls (2 mm d_{50} sediment).

It can be seen that the scouring has occurred but with some evidence of the abutment stone backfill slipping into the area where material is dislodged. This then has protects the existing foundation but encourages more constriction scour, especially as an additional flood wave passes.

The dotted line shows the extent of upstream scouring. Figure 4 shows the effect of wing wall placement on the overall depth of scour along the line of maximum scour. The bridge upstream face is located at the position of 500 mm, whereas the downstream face is at 800 mm. These are shown as dotted lines.

It is clear that the maximum depth of scour is less encouraged underneath the bridge in the presence of wing walls. However, further studies will determine the additional risk to other locations around the structure to determine scour depths relative to the maximum depth of scour.

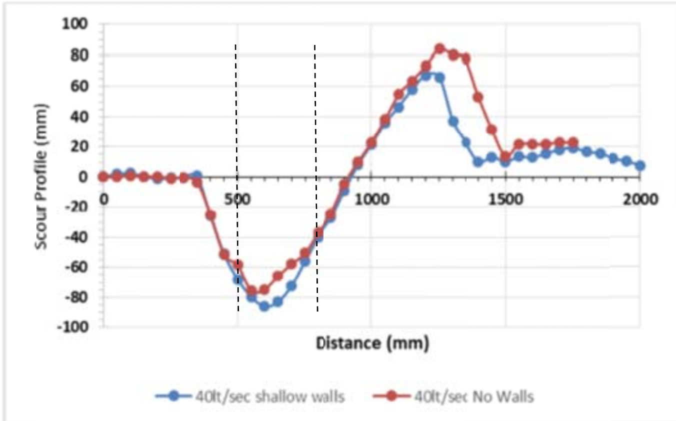

Figure 4: Longitudinal profile of scour hole along the line of maximum scour (40 l/s with 2 mm d_{50} sediment).

3.3. Current Scour prediction theories.

It was reported earlier in this paper that Lyn [10] revised equation 5 to proposed equation 6 as a means of determining scour depth under pressurised flow conditions. When the predictions from the HEC-18 equation are plotted against the current experimental data in Figure 5 it is clear that the scour depth from data produced for tests within the current study is reasonably close to the HEC-18 equation at the lowest discharge, but rapidly begins to move well above these predicted values as the discharge is increased. However, it is a concern that the HEC-18 equation predicts that the depth of scour decreases with a rise in discharge/velocity. When considering the same, a non-dimensionalised variable appears twice within the HEC-18 equation. It has been cited by Lyn [10] that there were issues with the same, and that unsatisfactory features were evident within the equation.

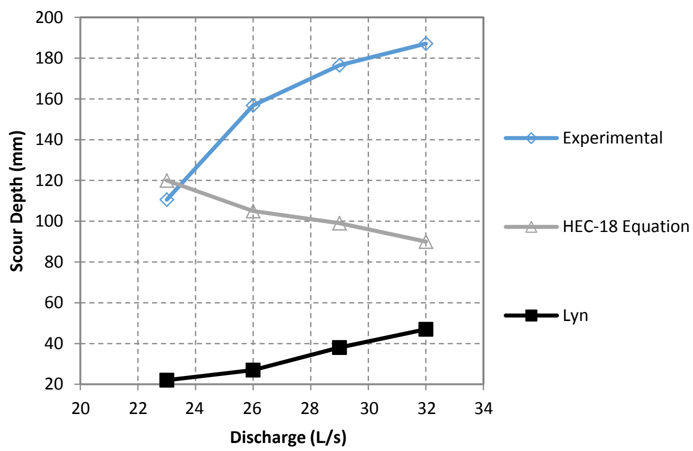

Figure 5: Comparison of experimental scour depths with existing equations (1.1 d_{50} sediment).

It is worth noting that the test results from Figure 5 relate to 1.1 mm d_{50} sediment. As the current study acquires further data, these observations will be further explored.

In relation to Lyn's [10] equation 6, there is an under-prediction of scour depth with discharge, therefore the present investigation will require the development of its own set of predictive equations. This is due to the three-dimensional nature of the scour development, where the flow is constricted in both vertical and horizontal directions. Previous authors on pressurised flow only considered vertical constriction.

4 CONCLUSIONS

The experimental observations from this study have shown that there is an appreciable rise in the magnitude of flow velocities within the vicinity of the bridge structure under pressurised flow. These velocities give rise to enhanced scour depths that are demonstrating a degree of under-prediction by current standards, These current standards are based on US Federal Highways Agency Guidelines and UK DMRB guidelines. They do not take into account the combined horizontal and vertical constrictions experienced by arch bridges. Further work is therefore being carried out to make a more informed prediction of scour within the vicinity of arch bridge structures subjected to pressurized conditions

REFERENCES

[1] Committee on Climate Change, "Tackling Climate Change", [Online], available from https://www.theccc.org.uk/tackling-climate-change/. [Accessed 12/09/2015].

[2] Design Manual for Roads & Bridges, "The Design of Highway Bridges for Hydraulic Action", BA59/94 (1994). Department for Transport (UK).

[3] Design Manual for Roads & Bridges, "The Assessment of Scour and Other Hydraulic Actions at Highway Structures", BD 97/12 (2012). Department for Transport (UK).

[4] Kirby, A M, Roca, M, Kitchen, A, Escarameia, M, Chesterton, O J. "Manual on scour at bridges and other hydraulic structures, second edition (C742)". April 2015, CIRIA.

[5] Ryan, D. Hamill, G.A., McRobert, J. Smyth, W. "The hydraulics and resulting bed scour within the vicinity of submerged single span arch bridges". Proceedings of the Civil Engineering Research Association of Ireland, Belfast, 2014.

[6] Federal Highway Administation (USA), "Hydraulic Design of Safe Bridges, Publication No: FHWA-HIF-12-018, Department of Transport. April 2012.

[7] Biery P . F. and Delleur. W. Hydraulics of single-span arch bridge constrictions. Proc. Am. Soc. Civ. Engrs, J. Hydraulics Div, 1962, 88, HY2, March, 75-108.

[8] Arneson, L.A. and Abt, S.R., (1998). "Vertical contraction scour at bridges with water flowing under pressure conditions." Transportation Research Record. 1647, 10-17.

[9] Richardson , E.V., Davis, S.R., (2001) Evaluating Scour at Bridges, HEC-18, FHWA-NH-01-001, 4th Edition. US. D.O.T. Washington. DC.

[10] Lyn, D.A., (2008) "Pressure-Flow Scour: A Re-examination of the HEC-18 Equation". Journal of Hydraulic Engineering. 2008.134. pp 1015-1020.

[11] Guo, J., Kerenyi, K., Paga-Ortiz, J.E. "Bridge Pressure Scour for Clear Water Conditions". (2009) Report No: FHWA-HRT-09-041. U.S. Department of Transportation, Federal Highway Administration (FHWA).

[12] Laursen, E.M., 1960, "Scour at bridge crossings" Journal Hydraulic Division, American Society of Civil Engineering, v. 89, no. HY3.